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OVERVIEW OF ADVANCES IN THE APPLICATION OF LIQUID METAL DROPLETS IN TOKAMAKS

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ABSTRACT

- The use of liquid-metal in-vessel components (IVCs) in thermonuclear reactors is a promising approach to addressing plasma–wall interaction, particularly were plasma exposure risks material erosion. In tokamaks and other fusion devices, these IVCs can take the form of capillary-porous systems (CPS), droplet/jet injection systems, or thin liquid-metal films. Injection of droplets into plasma avoids the formation of short circuit of the current through the stream, distinguishing this configuration from alternative schemes. This report presents results of experimental study demonstrating the feasibility of a droplet flow arrangement, in which galinstan droplets are injected into a steady-state magnetized plasma in the PLM device, focusing on the electric charge acquired by droplets within a magnetic field.

BACKGROUND

- Solid PFM suffer erosion and damage under high heat plasma fluxes in fusion devices.
- Liquid metals can self-replenish; droplets may reduce current short circuit and local overheating of the plasma-fasing materials.
- Droplets injection may combine advantages of liquids with acceptable engineering of the injection system.

OVERVIEW OF STUDIES ON LMDs IN TOKAMAKS AND PLASMA DEVICES

- Limitations of lithium CPS (Li chemical activity, complex cooling systems etc.) leaded to a consideration the exploration of alternative liquid metals and droplets injection.
- Lithium ultrasonic injector development (e.g., for T-11M) achieved controlled droplet velocities of 2.8–6.4 m/s and stable performance.
- Gallium droplet limiter experiments demonstrated feasibility: droplets 2–4 mm at 2–5 m/s, stable plasma interaction, and low evaporation. Thermal analysis: droplet surface heating (100–200 ° C) far below gallium's boiling point (~2400 ° C), confirming minimal plasma contamination.

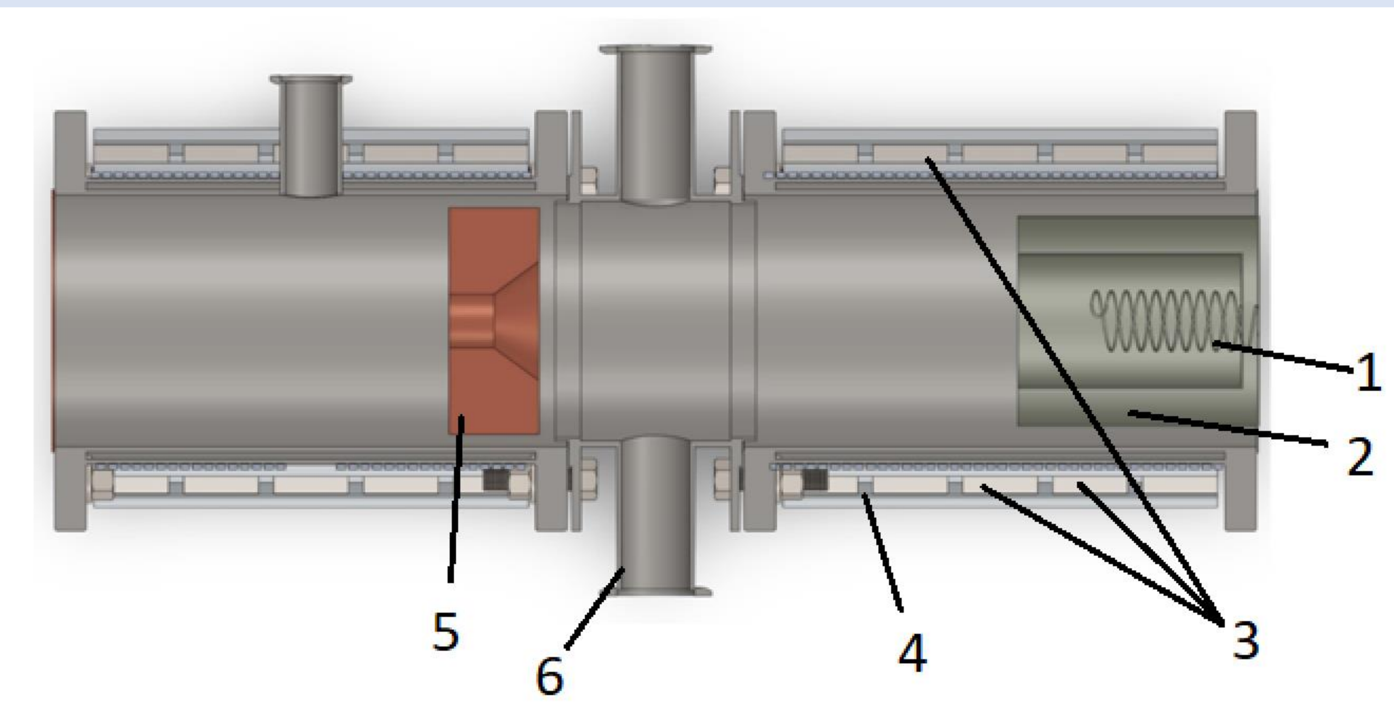

Fig. 1. Discharge chamber and magnetic system of the PLM plasma device: 1 — cathode; 3 — permanent magnets; 4 — solenoid; 5 — copper anode; 6 — diagnostic window

EXPERIMENTAL CHALLENGES AND METHODS

- Ensuring stability and controllability of liquid-metal droplets under magnetized plasma conditions.
- Measuring droplet charging and deformation to assess feasibility of protective properties.
- Experiments conducted at the PLM plasma device (NRU "MPEI") with Galinstan droplets injected into steady-state plasma (fig. 1).
- High-speed video diagnostics (120 fps) and image analysis to track droplet trajectory and shape changes.

OUTCOME

- Experimental results show that liquid metal droplets (Galinstan) can maintain stable form and controlled trajectories in steady-state magnetized plasma.
- Droplets acquire measurable electric charge (table 1), change shape toward spherical (fig. 2 a, b), and deviate in trajectory without significant evaporation or plasma contamination.
- These findings demonstrate that droplet injection is a feasible and controllable method for using in fusion devices.

TABLE 1. ESTIMATED DROPLET CHARGES AT VARIOUS PLASMA DISCHARGE CURRENTS IN THE PLM.

Plasma current, A	Charge estimated from the shape analysis, 10^{-7} C	Charge estimated from the trajectory analysis, 10^{-7} C
1	1.5	1.5
2	1.5	2.0
3	2.3	2.0
5	3.1	3.0
10	3.1	5.0
13.9	3.2	5.0

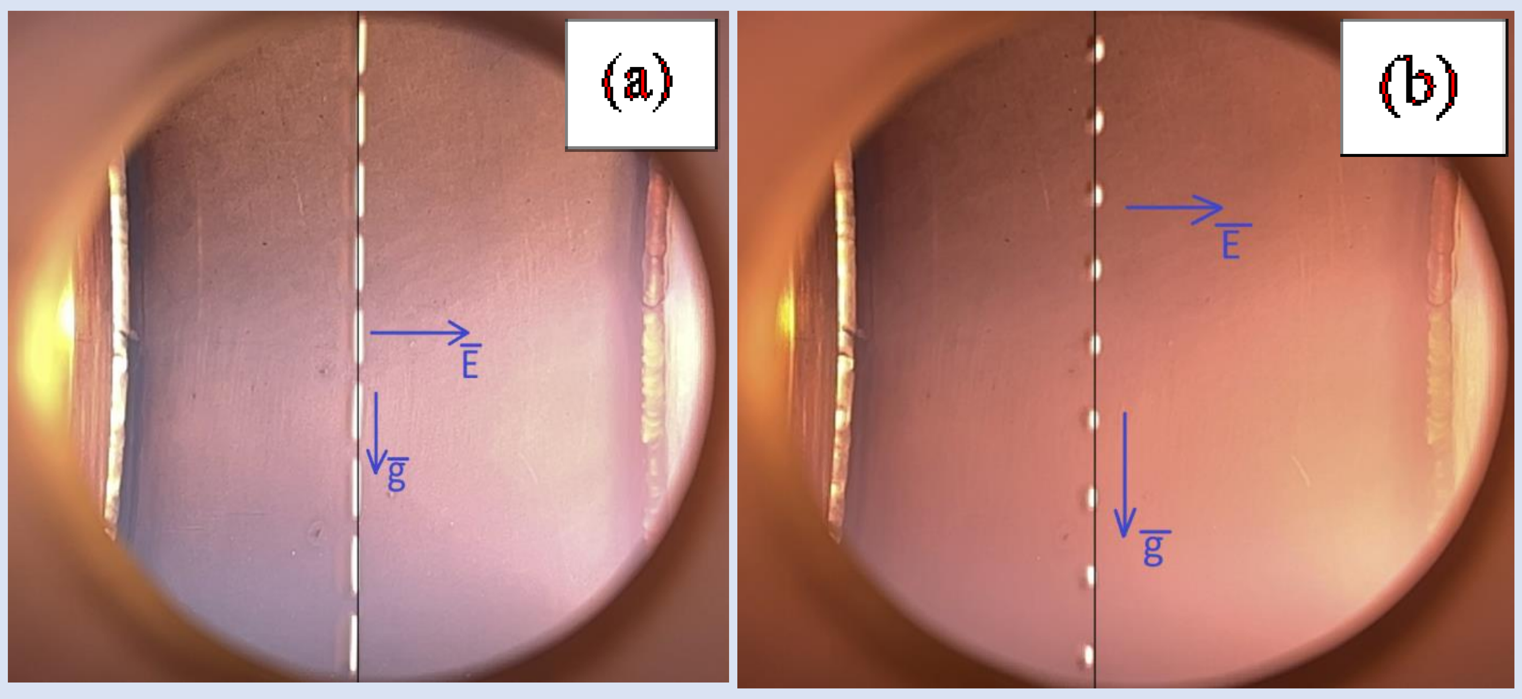

Fig. 2. Optical images of the droplets in the PLM plasma, observed through the horizontal diagnostic window, at discharge currents: (a) I = 1 A; (b) I = 10 A;

CONCLUSION

- The experiments confirm the feasibility of liquid metal droplet injection in magnetized plasma.
- For fusion reactor relevant conditions, the approach provides a promising pathway to address erosion and material lifetime challenges.
- Further experimental studies are necessary to investigate droplet dynamics, interactions with plasma and solid surface, and to optimize injection and collection systems for practical tokamak applications.

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